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PROTECTION OF THE MFTF ACCEL POWER SUPPLIES

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Summary

The MFTF experiment's Sustaining Neutral Beam Power Supply System (SNBPSS) includes twenty-four 95 kV, 80 A accel dc power supplies (ADCPS). Each power supply includes a relatively high-impedance (20 percent) rectifier transformer and a step voltage regulator with a 50-100 percent voltage range. With this combination, the fault current for some postulated faults may be lower than the supply's full load current at maximum voltage. A design has been developed which uses protective relays and current-limiting fuses coordinated to detect phase and ground faults, DC faults, incorrect voltage conditions, rectifier faults, power factor correction capacitor faults, and overloads. This unusual solution ensures fast tripping on potentially destructive high-current faults and long time delays at lower currents to allow 30 second pulse operation. The ADCPS meets the LLL specification that all major assemblies be self-protecting, that is, able to sustain external faults without damage and to minimize damage due to internal faults.

Introduction

Source voltage for the MFTF experiment is supplied by the P G & E Tesla substation at 230 kV. The supplied voltage is regulated to long-term variation of ± 3 percent and short-term variation of ± 1 percent. The Laboratory uses this power to feed two 60 MVA substation transformers which supply 13.8 kV to the Sustaining Neutral Beam Power Supplies. Fault delivery on the 230 kV line is 5376 MVA; at the LLL switchgear it is 750 MVA. In order to limit the destructive effects of ground faults, the University has provided system grounding through a 20Ω resistor, which limits ground fault current to 400 A. These systems are shown on Figures 1 and 2.

There are 24 accel dc power supplies located in the area immediately to the west of the 230 kV substation. These power supplies convert the 13.8 kV ac input into a direct voltage of 35 to 80 kV and deliver 10 to 88 A dc. Each power supply consists of a switchgear assembly, a step voltage regulator, a rectifier transformer, power factor correction capacitors and a rectifier assembly. The schematic is shown as Figure 3. Distribution of primary ac voltage follows practices to minimize both exposure to the elements and line-to-line faults. The 13.8 kV ac individually shielded cables are enclosed in 4" conduit in underground duct banks and use Elastimold-style insulated connectors to cover every apparatus bushing, up to and including the input of the rectifier transformer. These lines run at a full-load current of 390 A. Exposed buswork first appears at the secondary terminals of the rectifier transformer. Overhead tubular aluminum conductors

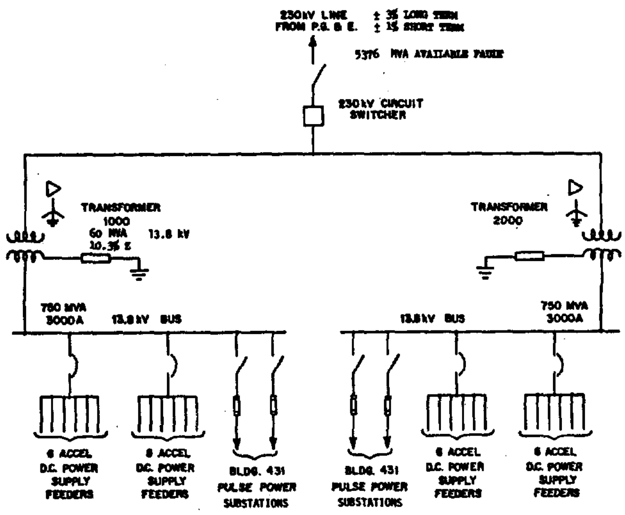

Figure 1

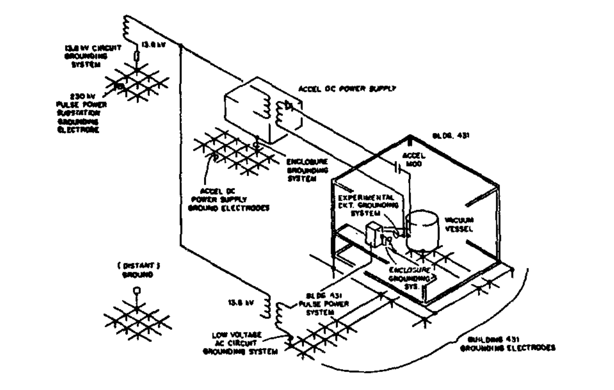

Figure 2

run through the series power factor correction units to the input of the rectifier assembly. The final output of the ADCPS from the rectifier is carried in shielded 120 kV dc cable that runs to the modulator in Building 431.

The switchgear assembly includes an outdoor enclosure. In addition to an electrically operated, visible, load interrupter switch, the enclosure houses monitoring equipment, transient protection equipment, circuit breaker for fault interruption, and on/off switching.

The load-interrupter switch is an air-break, three-pole unit, rated for continuous current of 600 A (full load current = 390 A) with a momentary fault rating of 40,000 A (available fault 38,000 A momentary). The switch is designed for repeated

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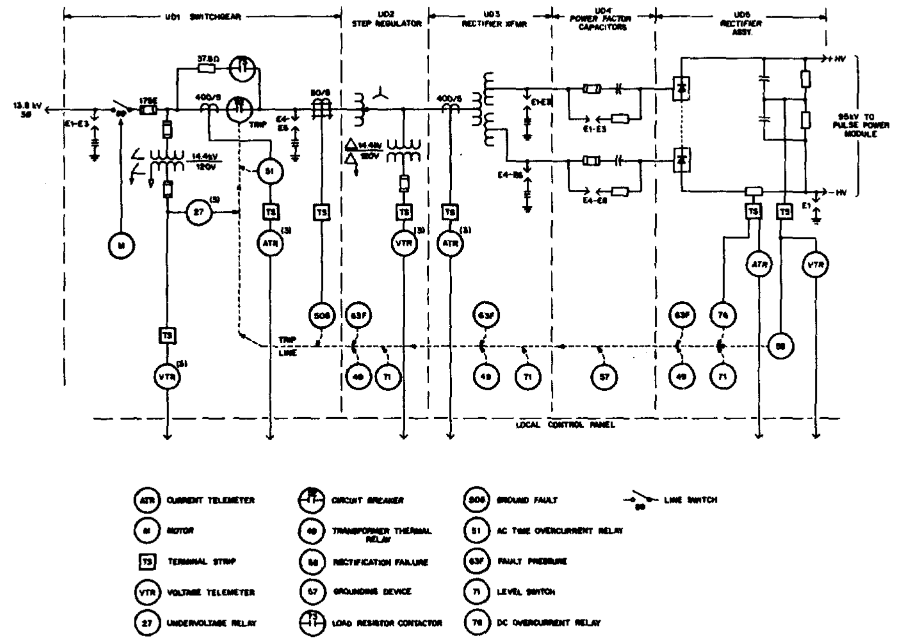

Figure 3

full-load interruption but has no manufacturer's rating at greater than full-load interruption. In this system, the switch is used as a zero-current disconnect switch. It is electrically operated and is mounted in the switchgear cabinet adjacent to a reinforced viewing window for visual verification of switch position.

The switchgear primary protection uses general purpose, current-limiting (CL) fuses rated at 13.8 kV, 175 A full-load capability (175 E fuse characteristics). This type of fuse not only interrupts the high fault currents, but also interrupts low fault currents down to approximately twice its continuous rating. In this application it operates during the "pulse-on" condition at over 200 percent of full load rating. During the crowbar "on" interval, it is subjected to over ten times normal rating. The "minimum melt time" curves for the CL fuses (Figure 4) indicate that both of these operating conditions fall within the safe "no damage boundary" of the fuse.

Power control for the rectifier transformer is achieved with the load resistor contactor (Device Number 75) and circuit breaker (52) combination (see Figure 3). The vacuum contactor used in conjunction with a set of series resistors (38 Ω per phase) limit the transformer inrush current to approximately 150 A rms. The ac circuit breaker assembly includes a stored-energy operating mechanism that will assure a contact parting time of approximately 10 ms from the time the trip coil is energized. The circuit breaker has a nominal current rating of 1200 A; it is rated for a minimum 10,000 mechanical operations, and a lifetime of 5000 interruptions at an interrupting current of 5000 A.

To achieve a coarse adjustment of the specified 30 to 80 kV dc output of the accel modulator, the step voltage regulator varies the ac input in discrete steps. The regulator is a design variation of a standard utilities' unit and includes a 32-step, 3-phase load tap changer that can make full-load step changes. The step regulator differs from the standard utilities' version in its range of 100-50 percent output to meet the required dc output voltage and its structural design for repeated crowbar operations.

The rectifier transformer operates on an input voltage of 6.6 to 13.1 kV and a line current of 390 A. The no-load output voltage is 35,300 V with 13.1 kV input. The full-load output current is 74 A rms. It has 20 percent nominal reactance on an 8.1 MW base. The rectifier transformer has two equal output-voltage secondaries, one wye-connected and one delta-connected.

The rectifier assembly consists primarily of two sets of three-phase, full-wave diode bridge assemblies, commutating networks, and dc output resistor-capacitors. These components are assembled in a single, oil filled steel tank, having cover busings to handle the input and output terminations. The rectifier tank is self-cooling, and uses oil-to-air integral radiators. The range of input voltages on each bridge is from 17.6 kV to 35.3 kV for total output dc voltage levels of 45 - 95 kV.

The rectifier is rated to meet the 2.5 times PIV (peak inverse voltage) rating given by the LLL specification at a reference level which is increased to account for the stored energy in the power factor correction network. The PIV rating is more than 3 in relation to the dc output. The supply reactance of the system driving the rectifiers is specified to limit peak fault current to about 5 times normal full load current. Coordinating this fault current with a high-speed breaker interruption of less than 25 milliseconds establishes the surge-current rating of the rectifiers.

A high-voltage resistive divider provides a dc voltage drive signal for a panel meter. The near ground end (negative return) of the dc output is limited to 5 kV excursions by a spark gap.

Protection Philosophy

The protection method used throughout the ADCPS is the provision of positive primary relaying combined with backup protection which operates if the primary device should fail to clear the fault. Each piece of protective equipment is coordinated with the operating requirements of the protected equipment, as well as with the other protective equipment as shown on the time current curves (Figure 4).

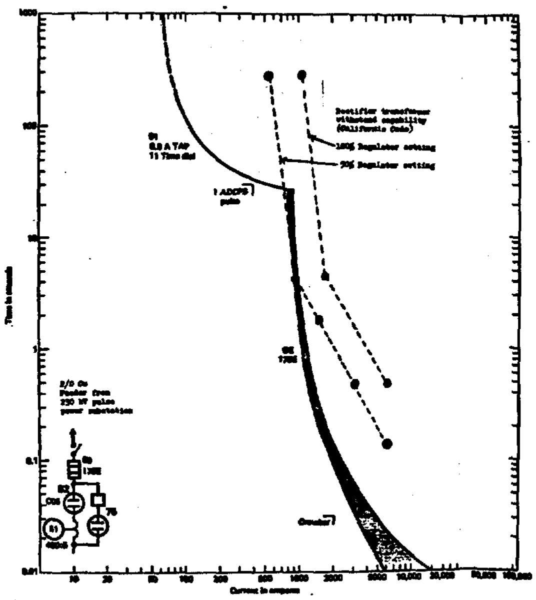

Figure 4

Primary protection for the switchgear includes current-limiting fuses and phase over-current and ground fault relays. Phase over-current is detected through three 400/5 current transformers, each feeding Westinghouse CO-5, long-time relays (one relay per phase). Ground fault current is sensed with a 50/5 zero-sequence window-type current transformer which feeds a Westinghouse-type SC instantaneous overcurrent relay.

Back-up protection is supplied by the 230 kV substation's phase over-current and under-voltage protection and the substation's neutral over-current detection.

Coordination of the over-current relaying for the step regulator, rectifier transformer and rectifier assembly is similar. Primary relaying can be divided into two types. Some protection is wired into the permissive-to-close circuit of the disconnect switch as well as the breaker trip circuit, while other protection is wired only into the trip circuit. The protective devices for oil temperature and oil level are in the first category. The sudden-pressure relay and the ground fault relay are in the second. Back-up relaying for these pieces of equipment consists of three device types located in the switchgear: phase over-current relays, current-limiting fuses and under-voltage-relays.

In addition to these, the rectifier assembly is equipped with ripple over-voltage detection to sense phase failures in either the power-factor correction network or the diode stacks.

The accel dc power supply uses capacitors in series with each phase of the rectifier transformer's output winding to correct the lagging power factor. The exact capacitance (18.3 μf) and voltage rating (13 kV rms) have been verified through computer-aided analysis. These capacitors are in series resonance with all inductive reactance in the system (including the 230 kV supply source) and produce a nominal 100 percent power factor with all 24 power supplies in simultaneous operation. The capacitors include: voltage-limiting shunt arc-gaps set at 30 kV equipped with current-limiting resistors, expulsion fuses in series with each capacitor module (to prevent overheating and rupture in the event of a shorted capacitor), and grounding hooks for personnel safety during maintenance. The spark gaps are set to fire at a given overload voltage (30 kV) resulting from the reactive current drop across the capacitors. Once the spark gaps fire, the capacitors are shorted. Their reactance is removed from the circuit, and the fault current is then limited by the leakage reactance of the transformer and primary source.

ADCPS Control

Control information reaches the equipment from two sources: main control function from the LLL supervisory computer located 1000 feet away, and local control. Command, monitor and trip signals are transmitted over fiber-optic data links. Trip signals are also duplicated over hard-wired links for backup protection. In addition, the hard-wired link provides a trip-free function. A relay circuit is provided which allows the circuit breaker (52, Figure 3) to close only once for each time the hard-wired link is activated. This prevents the switchgear from tripping repeatedly to close into a fault after a fault trip.

At each ADCPS there is a local control panel. From this position, it is possible to operate and monitor the supply for test purposes.

All commands to the ADCPS for ac circuit closure and for change in step regulator position originate in the SNBPSS control system located in Building 431. The local control panel requires commands from the SNBPSS control. Commands will not be transmitted if unsafe conditions exist within Building 431. Commands will not be accepted if faults or open interlocks, such as low oil level or excessively high temperature, exist in the ADCPS. In most cases redundant protection is provided by the microprocessor and the hard-wired relaying.

Coordination

Crucial to the protection of any circuit is an understanding of the operating characteristics of the circuit and the damange characteristics of the equipment to be protected. Another important consideration to keep in mind is that the location in the circuit of the sensing element will affect the indications received. In other words, a fault indication at one point will not necessarily be a fault indication at another.

The tool that is used extensively in the power industry to coordinate protective devices is the time-current characteristic graph (Figure 4). This is a plot of the operating requirements of the circuit, the damage curves of the equipment, and finally, the curves of the protective relaying and fusing which assure adequate protection.

The plot farthest left on Figure 4 shows the operating characteristics of the accel dc power supply as viewed from the switchgear where the fuses, current transformers, and relays are located. At the bottom of the graph or for the shortest time is the crowbarring of the power supply output. This draws 1700 A and lasts until the ac circuit breaker opens, about 30 ms. The next step is the normal pulse operation of the supply. During this, which will last up to 30 seconds, the ac phase current will be 390 A. Finally, the continuous rating of the smallest piece of equipment is plotted. In this case the rectifier-transformer is rated at 3000 kVA at 13.1 kV, which gives a line current of 132 A. Between the location of the current transformers in the switchgear, and the rectifier transformer is the step voltage regulator. If the regulator is at the 50 percent tap position the 132 A primary current in the rectifier transformer will be 66 A through the switchgear. Consequently our line on the time-current plot is from 30 seconds upward at 66 A.

The next important information to plot is the damage curves for the equipment to be protected. The California State Building Standards Electrical Code gives fault withstand vs. time requirements. These are plotted for the transformer. Since our transformers are both rated at 3000 kVA, their plots will coincide. The transformer plot is repeated because the regulator could be set at the 50 percent position (which would halve the current sensed in the switchgear).

Since the capacitors are removed from the circuit by spark gaps, they are not included. The rectifier assembly is not on the plot because the damage curve is off the paper to the right due to the current-limiting effect of the 20 percent impedance of the rectifier transformer.

After the operating requirements are plotted and the damage limits have been determined all that is left to do is to select protective equipment whose characteristics will fit between their plots.

The manufacturers of fuses and overcurrent relays publish time vs. current plots of their devices. From these can be selected the devices whose curves best match the requirements of the circuit. For the MFTF accel dc power supplies, the General Electric EJO-175-a fuse was selected. To complement the fuse, a Westinghouse C 05, long time over-current relay was selected. It was determined that a .8 A tap would be used with a time dial setting of 11. As the completed Figure 4 shows, this combination of fuse and over-current relays protect the power supply from damage during its entire operation.

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